APPLICATION

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TITLE: SPATIAL MULTIPLEXING WITH ANTENNA AND
                CONSTELLATION SELECTION FOR CORRELATED
                MIMO FADING CHANNELS

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SPATIAL MULTIPLEXING WITH ANTENNA AND CONSTELLATION SELECTION FOR CORRELATED MIMO FADING CHANNELS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This application claims priority to U.S. Provisional Application Serial No. 60/432,126, filed on December 9, 2002.

BACKGROUND

[0002]   Multi-element antenna systems, including multiple-input multiple-output (MIMO) systems, may increase the capacity and diversity in wireless communication systems. Several communication techniques, including space-time coding and spatial multiplexing, have been developed to exploit the potential of MIMO systems. Spatial multiplexing focuses on the rate advantage whereas space-time coding focuses on the diversity advantage of MIMO systems.

[0003]   Most MIMO systems use a statistical channel model that is an idealized abstraction of spatial propagation characteristics and assumes independent and identically distributed (i.i.d.) fading between different transmit-receive antenna pairs. In practice, however, the channel

coefficients between different transmit-receive antenna pairs may exhibit correlation due to closely spaced antennas and clustered scattering typical in realistic environments. In such conditions, the capacity of MIMO channels can be substantially lower, depending on the level of correlation.

SUMMARY

[0004] A multiple-in multiple-out (MIMO) system may use an antenna selection operation to determine an optimum number and subset of active antennas for communication over correlated fading channels. The system may use second-order statistics, such as correlation matrices determined at a receiver, to determine the optimal number of antennas. Each of the active antennas may have the same data rate and be allocated substantially equal power.

[0005] The optimum number of antennas may be selected to maximize a minimum signal-to-noise ration (SNR) margin. For a ZF (Zero Forcing), MMSE (Minimum Mean Square Error), or V-BLAST (Vertical Bell Laboratories Layered Space-Time) detection scheme, the number M_T and element indices p of active transmit antennas may be selected such that

$$(M_T, p) = \arg\max_{(\tilde{M}_T, \tilde{p})} \frac{\lambda_{\min}(R_T(\tilde{M}_T, \tilde{p}))}{\tilde{M}_T(2^{b_T/\tilde{M}_T} - 1)} \cdot \bar{\lambda}_{\min}(H_w^*(K_R, \tilde{M}_T)H_w(K_R, \tilde{M}_T)) .$$ For a

successive cancellation receiver (SCR) detection scheme, the number M_T and element indices p of active transmit antennas may be selected such that

$$(M_T, p) = \arg\max_{(\widetilde{M}_T, \widetilde{p})} \left\{ \begin{array}{l} \dfrac{1}{\widetilde{M}_T} \left[\ln\det\left(R_T(\widetilde{M}_T, \widetilde{p})\right) + \sum_{j=1}^{\widetilde{M}_T} \sum_{i=1}^{K_R - j} \dfrac{1}{i} - b_T \ln 2 \right] \\ - \ln \widetilde{M}_T \end{array} \right\} .$$

BRIEF DESCRIPTION OF THE DRAWINGS

[0006]   Figure 1 is a block diagram of a multi-element antenna system according to an embodiment.

[0007]   Figure 2 is a flowchart describing an antenna selection operation.

[0008]   Figure 3 is a plot illustrating a performance of the system of Figure 1 using all antennas and a subset of antennas in a first scenario.

[0009]   Figure 4 is a plot illustrating a performance of the system of Figure 1 using all antennas and a subset of antennas in another scenario.

DETAILED DESCRIPTION

[0010]   Fig. 1 illustrates a wireless multiple-in-multiple-out (MIMO) communication system 100, which includes a first transceiver 105 with multiple antennas 110

and a second transceiver 115 with multiple antennas 120.
In an embodiment, transceiver 105 has K_T transmit antennas
and transceiver 115 has K_R receive antennas, forming a K_R x
K_T MIMO system. The transceivers may each include an RF
(Radio Frequency) processor 125 and a baseband processor
130 The RF processor 125 may up-convert baseband signals
from the baseband processor 130 for transmission and down-
convert received signals to baseband signals for processing
by the baseband processor 130. The transceivers and
antennas in the system may be fixed or have low mobility.

[0011]   For the description below, the first transceiver
105 is designated as a "transmitter" because the first
transceiver 105 predominantly transmits signals to the
second transceiver 115, which predominantly receives
signals and is designated as a "receiver". Despite the
designations, both transmitter 105 and receiver 115 may
transmit and receive data.

[0012]   The multiple antennas may achieve high data rates
by using a transmission signaling scheme called "spatial
multiplexing," where a data bit stream may be demultiplexed
into parallel independent data streams. The independent
data streams are sent on different transmit antennas 110 to
obtain an increase in data rate according to the number of
transmit antennas 110 used.

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[0013]   The transmit antennas 110 may transmit signals in
a medium 140. The medium may include scatterers 145, e.g.,
buildings and geological features. The propagation
characteristics of the medium may be represented by a
matrix H in a channel model.

[0014]   Most MIMO systems use a statistical channel model
that is an idealized abstraction of spatial propagation
characteristics and assumes independent ad identically
distributed (i.i.d.) fading between different transmit-
receive antenna pairs. Idealized channel models may
facilitate capacity analysis and space-time coding
operations. In practice, however; the channel coefficients
between different transmit-receive antenna pairs exhibit
correlation due to closely spaced antennas and clustered
scattering typical in realistic environments. In such
conditions, the capacity of MIMO channels can be
substantially lower, depending on the level of correlation.

[0015]   Correlation refers to the degree to which two
variables are related to each other. A correlation
coefficient of 1 may indicate the two variables are very
correlated, e.g., if one has a high value, the other will
also have a high value, whereas a correlation coefficient
of 0 may indicate that the variables are relatively
independent. Correlation between symbols transmitted (and

received) by different antennas in communication channels tends to be inversely proportional to the spacing between antennas and the number of scatterers.

[0016]   The transmitter 105 and receiver 115 in the MIMO system 100 may communicate over correlated fading channels. In an embodiment, the transmitter 105 may transmit at a fixed data rate (b_T bps/Hz) with equal power allocated to each transmit antenna.

[0017]   The transmitter 105 and/or the receiver 115 may include an antenna selection module 150.   The antenna selection module at one of the transceivers may perform an antenna selection operation 200 to select a subset of antennas at the transmitter and receiver, as shown in Figure 2.   After antenna selection, $M_T \leq K_T$ transmit and $M_R \leq K_R$ receive antennas are used, with b_T/M_T bps/Hz being sent through each of the M_T active transmit antennas.   The antenna selection operation may select an optimum number of transmit antennas and corresponding symbol constellations using channel correlation matrices.   The channel correlation matrices are second-order statistics of the propagation medium 140, which change much more slowly than the actual fading of the channels themselves.   Since the second-order statistics are relatively stable, the correlation matrixes may be determined using long term

averaging. This may alleviate the need to frequently update the configuration of active antennas in the system.

[0018]   A model for the M_R X M_T channel matrix $H(M_R, M_T, q, p)$, where p and q denote the indices of the active transmit and receive antennas, respectively, is given by:

[0019] $$H(M_R, M_T, q, p) = R_R^{1/2}(M_R \cdot q) H_w, (M_R, M_T) R_T^{1/2}(M_T, p) \qquad (1)$$

[0020]   where $R_T(M_T, p)$ and $R_R(M_R, q)$ denote the correlation matrices among the active transmit and receive antennas, respectively, and $H_w(M_R, M_T)$ is an M_R X M_T matrix whose elements are independent and identically distributed complex Gaussian random variables with zero mean and unit variance

[0021]   The criterion used for selection of the antennas may be maximization of the minimum signal-to-noise ratio (SNR) margin. SNR_{min} denotes the minimum post-processing SNR among all M_T data substreams. A "post-processing" SNR refers to the SNR derived after data from multiple antennas are combined, as opposed to a "pre-processing" SNR derived from data at each antenna. The receiver may use any of a number of detection schemes to determine SNR_{min}. ZF (Zero Forcing), MMSE (Minimum Mean Square Error), and V-BLAST (Vertical Bell Laboratories Layered Space-Time) are all well known detection schemes.

[0022]   In an embodiment, b_T/M_T bps/Hz are allocated on each of the M_T active transmit antennas. Under this condition, the minimum SNR margin is given by

[0023] $$\lambda_{min} = \frac{SNR_{min}}{\Gamma(2^{b_T/M_T} - 1)}$$ (2)

[0024]   where Γ is the SNR gap from capacity, which is nearly constant for most spectral efficiencies encountered in practice.

[0025]   For a receiver using ZF, MMSE, or V-BLAST detection,

[0026] $$SNR_{min} \geq \frac{E_S}{M_T N_O} \lambda_{min}(H^*H)$$ (3)

[0027]   where E_s is the total transmit energy and $\lambda_{min}(A)$ is the minimum eigenvalue of a square matrix A.

[0028]   The lower bound for SNR_{min} is given by

[0029] $$SNR_{min} \geq \frac{E_S}{M_T N_O} \lambda_{min}(R_R)\lambda_{min}(R_T(M_{T,p}))$$
$$\cdot \lambda_{min}(H_w^*(K_R,M_T)H_w(K_R,M_T))$$ (4)

[0030]   The active transmit antennas are selected to maximize the minimum SNR margin. From (2) and (4), we have

[0031] $$\gamma_{min} \geq \frac{E_s\lambda_{min}(R_R)\lambda_{min}(R_T(M_T,p))}{\Gamma M_T N_0(2^{b_T/M_T} - 1)}$$
$$\cdot \lambda_{min}(H_w^*(K_R,M_T)H_w(K_R,M_T))$$ (5)

[0032]   The number M_T and element indices p of active transmit antennas are selected (block 205) such that

[0033]
$$(M_T, p) = \underset{(\tilde{M}_T, \tilde{p})}{\arg\max} \frac{\lambda_{\min}(R_T(\tilde{M}_T, \tilde{p}))}{\tilde{M}_T(2^{b_T/\tilde{M}_T} - 1)}$$

$$\cdot \bar{\lambda}_{\min}(H_w^*(K_R, \tilde{M}_T) H_w(K_R, \tilde{M}_T)) \tag{6}$$

[0034]   This may be determined by evaluating equation (6) for $M_T = 1$ to K_T.

[0035] $\bar{\lambda}_{\min}(H_w^*(K_R, \tilde{M}_T) H_w(K_R, \tilde{M}_T))$ is the mean of the minimum

eigenvalue of $H_w^*(K_R, \tilde{M}_T) H_w(K_R, \tilde{M}_T)$. The means can be stored

in lookup tables for different parameters of K_R and M_T.

[0036]   Once the optimum number of antennas is

determined, the actual antennas in the subset may be

selected (block 210). The active antennas at the

transmitter 105 and the receiver 115 may be selected to

provide the largest spacing between adjacent antennas in

the antenna array to further minimize correlation.

[0037]   The constellation for transmission is then

selected (block 215). The constellations may be selected

from, e.g., binary phase shift keying (BPSK), quadrature

phase shift keying (QPSK), 8-point phase shift keying (8-

PSK), 16-point quadrature amplitude modulation (16-QAM) and

64-QAM. The number of points transmitted, and hence, the

constellation for the antennas, may be determined from

$(2^{b_T/M_T})$. Once the antennas are selected, the transmitter

105 may transmit b_T/M_T bps/Hz from each transmit antenna
(block 220).

[0038] As described above, antenna selection operation
200 may be performed at either the transmitter 105 or the
receiver 115. For example, the antenna selection module
150 at the receiver 115 may determine the correlation
matrices from signals received from the transmit antennas,
calculate M_T, and transmit the results to the transmitter
105. Alternatively, the receiver may transmit the
correlation matrices to the transmitter, which may use the
selection module 150 to calculate M_T. The active antenna
configuration may be updated by re-executing the antenna
selection operation 200. However, since the antenna
selection operation is based on second-order statistics,
and hence relatively stable, frequent updates may not be
necessary.

[0039] In an alternative embodiment, the system may
include a successive cancellation receiver (SCR) with a
fixed detection order and variable bit allocation across
substreams.

[0040] Let b_i, $i = 1,. . ., M_T$ denote the spectral
efficiencies allocated to each of the M_T active transmit
antennas. The optimization problem can be stated as
follows:

[0041]
$$\max_{(M_T,M_R,p,q,b_i):\sum_{i=1}^{M_T} b_i=b_T} \min_{i\in\{1,...,M_T\}} \gamma_i \qquad (7)$$

[0042]   where

[0043] $$\gamma_i = \frac{SNR_i}{\Gamma(2^{b_i}-1)} \qquad (8)$$

[0044]   is the SNR margin for the i-th substream.

[0045]   In the SCR system, the pair (M_T,p) may be chosen such that

[0046] $$(M_T,p) = \arg\max_{(\tilde{M}_T,\tilde{p})} \left\{ \frac{1}{\tilde{M}_T}\left[\ln\det\left(R_T(\tilde{M}_T,\tilde{p})\right)+\sum_{j=1}^{\tilde{M}_T}\sum_{i=1}^{K_R-j}\frac{1}{i}-b_T\ln 2\right] - \ln\tilde{M}_T\right\} \qquad (9)$$

[0047]   Once the optimal pair (M_T, p) is chosen, the bit allocation for each transmit antenna is determined as follows. For a given channel realization H_w,

[0048] $$b_{i|H_w} = \log 2\left(\frac{SNR_i}{\Gamma\gamma_i}\right) \qquad (10)$$

[0049] $$= \frac{b_T}{M_T}+2\log_2|\lambda_i(R)|-\frac{1}{M_T}\log_2\det(R*R) \qquad (11)$$

[0050]   for i = 1, . . ., M_T. Here $\gamma_t=\gamma_i, i=1,...,M_T$ and R is the upper triangular matrix obtained from the QR decomposition of the channel matrix H. The results are then averaged over several realizations of H_w and rounded to the nearest integer to obtain the final bit allocation bi, i = 1, . . .,M_T. If $\sum_{i=1}^{M_T}b_i \neq b_T$, the bit allocations before rounding that are close to an odd multiple of 0.5 are

rounded in the opposite direction until the desired spectral efficiency b_T is obtained. The constellation for the i-th active transmit antenna is selected such that b_i bps/Hz are transmitted.

[0051]   Simulations were performed to evaluate the performance of the antenna and constellation selection algorithms in correlated fading channels. In all the simulations, we use $K_T=K_R=6$ and uniform linear arrays with half-wavelength antenna spacing. Two scenarios of correlated fading are evaluated. Scenario 1 consists of i.i.d. fading. Scenario 2 has $R_R=I_{K_R}$ and two equally weighted transmit clusters with angles of departure and angle spreads given by $\widetilde{\theta}_{T,1} = \pi/6, \widetilde{\theta}_{T,2} = \pi/2, \sigma_{\theta_{t,1}} = \pi/30, \sigma_{\theta_{t,2}} = \pi/20$.

[0052]   The fixed data rate is chosen to be $b_T=12$bps/Hz. Uncoded transmission and the following signal constellations were considered: BPSK, QPSK, 8-PSK, 16-QAM, and 64-QAM. The various MIMO detection techniques are evaluated in terms of the bit error rate (BER) as a function of the average SNR, where SNR $\equiv E_s/N_o$.

[0053]   The mean value $\overline{\lambda}_{min}\left(H_{w'}^*(K_R, M_T)H_{w'}(K_R, M_T)\right)$ was determined using 100000 Monte Carlo simulations of complex Wishart matrices. Figure 3 is a plot of the BER performance for Scenario 1 (i.i.d. fading) of the MMSE, V-

BLAST and SCR receivers. As a result of antenna and
constellation selection. Antennas 1, 2, and 3 transmit a
16-QAM constellation for the linear and V-BLAST system.
For the SCR system, Antennas 1 through 5 are active with
transmit constellations 8-PSK,8-PSK, QPSK, QPSK, and QPSK,
respectively. Figure 3 illustrates that even for i.i.d.
fading, there is a significant performance gain for all
three receivers by using a subset of the K_T available
transmit antennas with higher order constellations compared
to activating all transmit antennas with lower order
constellations. When all transmit antennas are active,
error propagation causes the V-BLAST receiver to perform
worse than the MMSE receiver at low to moderate SNRs. The
bit allocation is uniform for the SCR system when all
transmit antennas are active. When a subset of active
transmit antennas is used, the constellation size decreases
as the antenna index increases since the transmitted data
are estimated by the SCR receiver in decreasing order of
the antenna index.

[0054]   The BER performance for Scenario 2 is plotted in
Figure 4. After antenna and constellation selection,
Antennas 1 and 2 transmit a 64-QAM constellation for the
linear and V-BLAST systems. For the SCR system, Antennas
1, 2, 5, and 6 are active with transmit constellations 16-

QAM, 8-PSK, 8-PSK, and QPSK, respectively. As in Scenario 1, a large performance gain is observed by activating a subset of transmit antennas. Because of the relatively high transmit antenna correlation for Scenario 2, error propagation causes the V-BLAST and SCR receiver to perform worse than the MMSE receiver when all transmit antennas are active.

[0055]   The use of second-order statistics, such as channel correlation matrices, for antenna and constellation selection have been described. These second-order statistics are related to signal variance in the medium. In alternative embodiments, other higher-order statistics of the propagation medium may also be used for antenna and constellation selection. These higher order measures may include, for example, third-order statistics (third-order cumulant and bispectrum), which are related to the signal skewness, and fourth-order statistics (fourth-order cumulant and trispectrum), which are related to the signal kurtosis. Like the second-order statistics, these other higher order statistics of the propagations medium may change much more slowly than the actual fading of the channels themselves

[0056]   A number of embodiments have been described. Nevertheless, it will be understood that various

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modifications may be made without departing from the spirit and scope of the invention. For example, blocks in the flowchart may be skipped or performed out of order and still produce desirable results. Accordingly, other embodiments are within the scope of the following claims.